Chapter 6

Conclusion and Future Work

6.1 Summary of the results

6.2 Future work

One of our previous contributions trigger a CVE¹ on the code generation component of wasmtime, highlighting that even when the language specification is meant to be secure, the underlying host implementation might not be.

TODO Side channel reproduction and study of the impact of side-channel

6.2.1 wasm-mutate future work

TODO Obfuscation and data augmentation

 $^{^{1} \}verb|https://www.fastly.com/blog/defense-in-depth-stopping-a-wasm-compiler-bug-before-it-became-a-problem$

Bibliography

- [1] Stiévenart, Q., De Roover, C., and Ghafari, M. (2022). Security risks of porting c programs to webassembly. In *Proceedings of the 37th ACM/SIGAPP Symposium on Applied Computing*, SAC '22, page 1713–1722, New York, NY, USA. Association for Computing Machinery.
- [2] Romano, A., Lehmann, D., Pradel, M., and Wang, W. (2022). Wobfuscator: Obfuscating javascript malware via opportunistic translation to webassembly. In 2022 2022 IEEE Symposium on Security and Privacy (SP), pages 1101–1116, Los Alamitos, CA, USA. IEEE Computer Society.
- [3] Harrand, N. (2022). Software Diversity for Third-Party Dependencies. PhD thesis, KTH, Software and Computer systems, SCS. QCR 20220413.
- [4] Voulimeneas, A., Song, D., Larsen, P., Franz, M., and Volckaert, S. (2021). dmvx: Secure and efficient multi-variant execution in a distributed setting. In *Proceedings of the 14th European Workshop on Systems Security*, pages 41–47.
- [5] Spies,B. and Mock,M. (2021). An evaluation of webassembly in non-web environments. In 2021 XLVII Latin American Computing Conference (CLEI), pages 1–10.
- [6] Narayan,S., Disselkoen,C., Moghimi,D., Cauligi,S., Johnson,E., Gang,Z., Vahldiek-Oberwagner,A., Sahita,R., Shacham,H., Tullsen,D., et al. (2021). Swivel: Hardening webassembly against spectre. In USENIX Security Symposium.
- [7] Lee,S., Kang,H., Jang,J., and Kang,B. B. (2021). Savior: Thwarting stack-based memory safety violations by randomizing stack layout. *IEEE Transactions on Dependable and Secure Computing*.
- [8] Johnson, E., Thien, D., Alhessi, Y., Narayan, S., Brown, F., Lerner, S., Mc-Mullen, T., Savage, S., and Stefan, D. (2021). Sfi safety for native-compiled wasm. NDSS. Internet Society.
- [9] Hilbig, A., Lehmann, D., and Pradel, M. (2021). An empirical study of real-world webassembly binaries: Security, languages, use cases. *Proceedings of the Web Conference* 2021.

- [10] Cabrera Arteaga, J., Laperdrix, P., Monperrus, M., and Baudry, B. (2021). Multi-Variant Execution at the Edge. arXiv e-prints, page arXiv:2108.08125.
- [11] Cabrera Arteaga, J., Floros, O., Vera Perez, O., Baudry, B., and Monperrus, M. (2021). Crow: code diversification for webassembly. In *MADWeb*, *NDSS* 2021.
- [12] (2021). Webassembly system interface.
- [13] (2021). National Cyber Leap Year.
- [14] Xu,Y., Solihin,Y., and Shen,X. (2020). Merr: Improving security of persistent memory objects via efficient memory exposure reduction and randomization. In *Proc. of ASPLOS*, pages 987–1000.
- [15] Wen, E. and Weber, G. (2020). Wasmachine: Bring iot up to speed with a webassembly os. In 2020 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops), pages 1–4. IEEE.
- [16] Tsoupidi,R. M., Lozano,R. C., and Baudry,B. (2020). Constraint-based software diversification for efficient mitigation of code-reuse attacks. *ArXiv* abs/2007.08955.
- [17] Shillaker, S. and Pietzuch, P. (2020). Faasm: Lightweight isolation for efficient stateful serverless computing. In *USENIX Annual Technical Conference*, pages 419–433.
- [18] Runeson, P., Engström, E., and Storey, M.-A. (2020). The Design Science Paradigm as a Frame for Empirical Software Engineering, pages 127–147. Springer International Publishing, Cham.
- [19] Mendki, P. (2020). Evaluating webassembly enabled serverless approach for edge computing. In 2020 IEEE Cloud Summit, pages 161–166.
- [20] Lehmann, D., Kinder, J., and Pradel, M. (2020). Everything old is new again: Binary security of webassembly. In 29th USENIX Security Symposium (USENIX Security 20). USENIX Association.
- [21] Harrand, N., Soto-Valero, C., Monperrus, M., and Baudry, B. (2020). Java decompiler diversity and its application to meta-decompilation. *Journal of Systems and Software*, 168:110645.
- [22] Gadepalli, P. K., McBride, S., Peach, G., Cherkasova, L., and Parmer, G. (2020). Sledge: A serverless-first, light-weight wasm runtime for the edge. In *Proceedings* of the 21st International Middleware Conference, page 265–279.
- [23] Chen,D. and W3C group (2020). WebAssembly documentation: Security. Accessed: 18 June 2020.

- [24] Cabrera Arteaga, J., Donde, S., Gu, J., Floros, O., Satabin, L., Baudry, B., and Monperrus, M. (2020). Superoptimization of WebAssembly Bytecode, page 36–40. Association for Computing Machinery, New York, NY, USA.
- [25] Bryant,D. (2020). Webassembly outside the browser: A new foundation for pervasive computing. In Proc. of ICWE 2020, pages 9–12.
- [26] Österlund,S., Koning,K., Olivier,P., Barbalace,A., Bos,H., and Giuffrida,C. (2019). kmvx: Detecting kernel information leaks with multi-variant execution. In ASPLOS.
- [27] Churchill, B., Padon, O., Sharma, R., and Aiken, A. (2019). Semantic program alignment for equivalence checking. In *Proceedings of the 40th ACM SIGPLAN Conference on Programming Language Design and Implementation*, PLDI 2019, page 1027–1040, New York, NY, USA. Association for Computing Machinery.
- [28] Cabrera Arteaga, J., Monperrus, M., and Baudry, B. (2019). Scalable comparison of javascript v8 bytecode traces. In *Proceedings of the 11th ACM SIGPLAN International Workshop on Virtual Machines and Intermediate Languages*, VMIL 2019, page 22–31, New York, NY, USA. Association for Computing Machinery.
- [29] Aga,M. T. and Austin,T. (2019). Smokestack: thwarting dop attacks with runtime stack layout randomization. In *Proc. of CGO*, pages 26–36.
- [30] Varda, K. (2018). Webassembly on cloudflare workers. Technical report.
- [31] Silvanovich, N. (2018). The problems and promise of webassembly. Technical report.
- [32] Lu,K., Xu,M., Song,C., Kim,T., and Lee,W. (2018). Stopping memory disclosures via diversification and replicated execution. *IEEE Transactions on Dependable and Secure Computing*.
- [33] Li, J., Zhao, B., and Zhang, C. (2018). Fuzzing: a survey. *Cybersecurity*, 1(1):1–13.
- [34] Jacobsson, M. and Wåhslén, J. (2018). Virtual machine execution for wearables based on webassembly. In *EAI International Conference on Body Area Networks*, pages 381–389. Springer, Cham.
- [35] Hickey,P. (2018). Announcing lucet: Fastly's native webassembly compiler and runtime. Technical report.
- [36] Genkin, D., Pachmanov, L., Tromer, E., and Yarom, Y. (2018). Drive-by key-extraction cache attacks from portable code. *IACR Cryptol. ePrint Arch.*, 2018:119.

- [37] Belleville, N., Couroussé, D., Heydemann, K., and Charles, H.-P. (2018). Automated software protection for the masses against side-channel attacks. *ACM Trans. Archit. Code Optim.*, 15(4).
- [38] Zalewski, M. (2017). American fuzzy lop.
- [39] WebAssembly Community Group (2017). WebAssembly Specification.
- [40] Sasnauskas, R., Chen, Y., Collingbourne, P., Ketema, J., Lup, G., Taneja, J., and Regehr, J. (2017). Souper: A Synthesizing Superoptimizer. arXiv preprint 1711.04422.
- [41] Oracle (2017). JDK 9 Release Notes. Deprecation of Java Applets.
- [42] Haas, A., Rossberg, A., Schuff, D. L., Schuff, D. L., Titzer, B. L., Holman, M., Gohman, D., Wagner, L., Zakai, A., and Bastien, J. F. (2017). Bringing the web up to speed with webassembly. *PLDI*.
- [43] Van Es,N., Nicolay,J., Stievenart,Q., D'Hondt,T., and De Roover,C. (2016). A performant scheme interpreter in asm.js. In *Proceedings of the 31st Annual ACM Symposium on Applied Computing*, SAC '16, page 1944–1951, New York, NY, USA. Association for Computing Machinery.
- [44] Phothilimthana, P. M., Thakur, A., Bodik, R., and Dhurjati, D. (2016). Scaling up superoptimization. SIGARCH Comput. Archit. News, 44(2):297–310.
- [45] Couroussé, D., Barry, T., Robisson, B., Jaillon, P., Potin, O., and Lanet, J.-L. (2016). Runtime code polymorphism as a protection against side channel attacks. In IFIP International Conference on Information Security Theory and Practice, pages 136–152. Springer.
- [46] Morgan, T. D. and Morgan, J. W. (2015). Web timing attacks made practical. Black Hat.
- [47] Davi, L., Liebchen, C., Sadeghi, A.-R., Snow, K. Z., and Monrose, F. (2015). Isomeron: Code randomization resilient to (just-in-time) return-oriented programming. In *NDSS*.
- [48] Crane, S., Homescu, A., Brunthaler, S., Larsen, P., and Franz, M. (2015). Thwarting cache side-channel attacks through dynamic software diversity. In NDSS, pages 8–11.
- [49] Baudry,B. and Monperrus,M. (2015). The multiple facets of software diversity: Recent developments in year 2000 and beyond. *ACM Comput. Surv.*, 48(1).
- [50] Alon Zakai (2015). asm.js Speedups Everywhere.

- [51] Agosta, G., Barenghi, A., Pelosi, G., and Scandale, M. (2015). The MEET approach: Securing cryptographic embedded software against side channel attacks. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, 34(8):1320–1333.
- [52] Zakai and colleagues (2014b). Emscripten.
- [53] Zakai and colleagues (2014a). asm.js.
- [54] Le, V., Afshari, M., and Su, Z. (2014). Compiler validation via equivalence modulo inputs. In Proceedings of the 35th ACM SIGPLAN Conference on Programming Language Design and Implementation, PLDI '14, page 216–226.
- [55] Okhravi, H., Rabe, M., Mayberry, T., Leonard, W., Hobson, T., Bigelow, D., and Streilein, W. (2013). Survey of cyber moving targets. Massachusetts Inst of Technology Lexington Lincoln Lab, No. MIT/LL-TR-1166.
- [56] Homescu, A., Neisius, S., Larsen, P., Brunthaler, S., and Franz, M. (2013). Profile-guided automated software diversity. In *Proceedings of the 2013 IEEE/ACM International Symposium on Code Generation and Optimization (CGO)*, pages 1–11. IEEE.
- [57] Jackson, T. (2012). On the Design, Implications, and Effects of Implementing Software Diversity for Security. PhD thesis, University of California, Irvine.
- [58] Cleemput, J. V., Coppens, B., and De Sutter, B. (2012). Compiler mitigations for time attacks on modern x86 processors. *ACM Trans. Archit. Code Optim.*, 8(4).
- [59] Sidiroglou-Douskos,S., Misailovic,S., Hoffmann,H., and Rinard,M. (2011). Managing performance vs. accuracy trade-offs with loop perforation. In Proceedings of the 19th ACM SIGSOFT Symposium and the 13th European Conference on Foundations of Software Engineering, ESEC/FSE '11, page 124–134, New York, NY, USA. Association for Computing Machinery.
- [60] Jackson, T., Salamat, B., Homescu, A., Manivannan, K., Wagner, G., Gal, A., Brunthaler, S., Wimmer, C., and Franz, M. (2011). Compiler-generated software diversity. In *Moving Target Defense*, pages 77–98. Springer.
- [61] Amarilli, A., Müller, S., Naccache, D., Page, D., Rauzy, P., and Tunstall, M. (2011). Can code polymorphism limit information leakage? In IFIP International Workshop on Information Security Theory and Practices, pages 1–21. Springer.
- [62] Chen, T. Y., Kuo, F.-C., Merkel, R. G., and Tse, T. H. (2010). Adaptive random testing: The art of test case diversity. J. Syst. Softw., 83:60–66.

- [63] Salamat,B., Jackson,T., Gal,A., and Franz,M. (2009). Orchestra: intrusion detection using parallel execution and monitoring of program variants in user-space. In *Proceedings of the 4th ACM European conference on Computer systems*, pages 33–46.
- [64] Maia, M. D. A., Sobreira, V., Paixão, K. R., Amo, R. A. D., and Silva, I. R. (2008). Using a sequence alignment algorithm to identify specific and common code from execution traces. In *Proceedings of the 4th International Workshop on Program Comprehension through Dynamic Analysis (PCODA*, pages 6–10.
- [65] Jacob, M., Jakubowski, M. H., Naldurg, P., Saw, C. W. N., and Venkatesan, R. (2008). The superdiversifier: Peephole individualization for software protection. In *International Workshop on Security*, pages 100–120. Springer.
- [66] de Moura, L. and Bjørner, N. (2008). Z3: An efficient smt solver. In Ramakrishnan, C. R. and Rehof, J., editors, Tools and Algorithms for the Construction and Analysis of Systems, pages 337–340, Berlin, Heidelberg. Springer Berlin Heidelberg.
- [67] Salamat,B., Gal,A., Jackson,T., Manivannan,K., Wagner,G., and Franz,M. (2007). Stopping buffer overflow attacks at run-time: Simultaneous multi-variant program execution on a multicore processor. Technical report, Technical Report 07-13, School of Information and Computer Sciences, UCIrvine.
- [68] Microsoft (2007). Silverlight.
- [69] Bruschi, D., Cavallaro, L., and Lanzi, A. (2007). Diversified process replicæ for defeating memory error exploits. In Proc. of the Int. Performance, Computing, and Communications Conference.
- [70] Younan, Y., Pozza, D., Piessens, F., and Joosen, W. (2006). Extended protection against stack smashing attacks without performance loss. In 2006 22nd Annual Computer Security Applications Conference (ACSAC'06), pages 429–438.
- [71] Cox,B., Evans,D., Filipi,A., Rowanhill,J., Hu,W., Davidson,J., Knight,J., Nguyen-Tuong,A., and Hiser,J. (2006). N-variant systems: a secretless framework for security through diversity. In *Proc. of USENIX Security Symposium*, USENIX-SS'06.
- [72] Pohl,K., Böckle,G., and Van Der Linden,F. (2005). Software product line engineering: foundations, principles, and techniques, volume 1. Springer.
- [73] Bhatkar, S., Sekar, R., and DuVarney, D. C. (2005). Efficient techniques for comprehensive protection from memory error exploits. In *Proceedings of the USENIX Security Symposium*, pages 271–286.

- [74] El-Khalil,R. and Keromytis,A. D. (2004). Hydan: Hiding information in program binaries. In Lopez,J., Qing,S., and Okamoto,E., editors, *Information and Communications Security*, pages 187–199, Berlin, Heidelberg. Springer Berlin Heidelberg.
- [75] Kc,G. S., Keromytis,A. D., and Prevelakis,V. (2003). Countering codeinjection attacks with instruction-set randomization. In *Proc. of CCS*, pages 272–280.
- [76] Bhatkar,S., DuVarney,D. C., and Sekar,R. (2003). Address obfuscation: an efficient approach to combat a board range of memory error exploits. In Proceedings of the USENIX Security Symposium.
- [77] Barrantes, E. G., Ackley, D. H., Forrest, S., Palmer, T. S., Stefanovic, D., and Zovi, D. D. (2003). Randomized instruction set emulation to disrupt binary code injection attacks. In *Proc. CCS*, pages 281–289.
- [78] Chew,M. and Song,D. (2002). Mitigating buffer overflows by operating system randomization. Technical Report CS-02-197, Carnegie Mellon University.
- [79] Microsoft (1996). Microsoft Announces ActiveX Technologies.
- [80] Cohen, F. B. (1993). Operating system protection through program evolution. Computers & Security, 12(6):565–584.
- [81] Pettis, K. and Hansen, R. C. (1990). Profile guided code positioning. In *Proceedings of the ACM SIGPLAN 1990 Conference on Programming Language Design and Implementation*, PLDI '90, page 16–27, New York, NY, USA. Association for Computing Machinery.
- [82] Henry,M. (1987). Superoptimizer: a look at the smallest program. *ACM SIGARCH Computer Architecture News*, 15(5):122–126.
- [83] Avizienis and Kelly (1984). Fault tolerance by design diversity: Concepts and experiments. *Computer*, 17(8):67–80.
- [84] Ryder, B. G. (1979). Constructing the call graph of a program. *IEEE Transactions on Software Engineering*, (3):216–226.
- [85] Needleman, S. B. and Wunsch, C. D. (1970). A general method applicable to the search for similarities in the amino acid sequence of two proteins. 48(3):443–453.
- [86] Gnanadesikan, R. and Wilk, M. B. (1968). Probability plotting methods for the analysis of data. *Biometrika*, 55(1):1–17.
- [87] Mann, H. B. and Whitney, D. R. (1947). On a test of whether one of two random variables is stochastically larger than the other. *Ann. Math. Statist.*, 18(1):50–60.
- [88] Cox,M. R. (1893). Cinderella: Three hundred and forty-five variants of Cinderella, Catskin, and Cap o'Rushes. Number 31. Folk-lore Society.